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**A STUDY OF THE BEHAVIOR OF VEHICLE
PLATOON UNDER NEW COMMUNICATION
TOPOLOGY**

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Master's Thesis

Supervisor

Asst. Prof. Dr. Hasan ABDULKADER

Istanbul, 2023

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The thesis titled A STUDY OF THE BEHAVIOUR OF VEHICLE PLATOON UNDER NEW COMMUNICATION TOPOLOGY prepared by RAGHDA TARIQ SALIH ALSALIH and submitted on 25/04/2023 has been **accepted unanimously** for the degree of Master of Science in Electrical and Computer Engineering.

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Signature

DEDICATION

To my cherished family, I dedicate my thesis. I value all that you have done for me to accomplish this thesis, including your love, prayers, care, time, encouragement, and support. Especially I am grateful to my amazing mother for her unending love and for always being there to help me on my journey, as well as to my gorgeous father for his unstoppable encouragement and support.



ABSTRACT

A STUDY OF THE BEHAVIOR OF VEHICLE PLATOON UNDER NEW COMMUNICATION TOPOLOGY

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The deployment of vehicle platooning as a solution to numerous issues with traffic flow, safety, fuel economy, and lowering carbon dioxide (CO₂) emissions has generated a lot of interest in research during the past years. This thesis proposes a new topology called BDOL to reduce communication costs because cost reduction is essential and vital to the business sector. Due to the fact that the BDOL topology is a relaxation of the BDL topology, it is less expensive than the BDL topology. First, a numerical comparison using BDL topology is used to demonstrate the dynamical system's string stability. After then, a thorough computer-based simulation was used to assess how well the suggested topology performed. Many vehicles are assembled into a homogeneous platoon that is tested on both straight and curved tracks while maintaining the minimally acceptable inter-vehicle spacing. We assessed our topology's performance and put its string stability to the test under various conditions. In addition to a platoon going on a straight track with or without disturbance, it is also explored how a curved track's velocity disturbance may affect the platoon. The outcomes show how successfully the suggested topology accomplishes the desired goals.

Keywords: Vehicle Platoon, Platoon Communication, Topologies, Disturbances, String Stability, SUMO.

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ABBREVIATIONS

CO2	:	Carbon Dioxide
AI	:	Artificial Intelligence
NHTSA	:	National Highway Traffic Safety Administration
PATH	:	Partners for Advanced Transit and Highways
ITS	:	Intelligent Transportation System
GCDC	:	Grand Cooperative Driving Challenge
SARTRE	:	Safe Road Trains for the Environment
DCHDVP	:	Distributed Control of a Heavy-Duty Vehicle Platoon
COMPANION	:	Cooperative Dynamic Formation of Platoons for Safe and Energy Optimized Goods Transportation
ENSEMBLE	:	Enabling Safe Multi Brand Platooning for Europe
VANET	:	Vehicular Ad-hoc Network
V2V	:	Vehicle-to-Vehicle
V2I	:	Vehicle-to-Infrastructure
WANET	:	Wireless Ad-hoc Network
MANET	:	Mobile Ad-hoc Network
RSU	:	Road Side Unit
GPS	:	Global Positioning System
IEEE	:	Institute of Electrical and Electronics Engineers
WAVE	:	Wireless Access in Vehicular Environment

DSRC	:	Dedicated Short Range Communication
FCC	:	Federal Communications Commission
CCH	:	Control Channel
SCH	:	Service Channels
CAMs	:	Cooperative Awareness Messages
BSMs	:	Basic Safety Messages
DENM	:	Decentralized Environmental Notification Message
LiDAR	:	Light Detection and Ranging
TOF	:	Time-of-Flight
RADAR	:	Radio Detection and Ranging
IFT	:	Information Flow Topology
PF	:	Predecessor Following
PLF	:	Predecessor Leader Following
BD	:	Bidirectional
BDL	:	Bidirectional Leader
TPF	:	Two-predecessors Following
TPLF	:	Two-predecessor Leader Following
BDOL	:	Bidirectional Odd Leader
SUMO	:	Simulation of Urban Mobility

LIST OF SYMBOLS

\mathcal{G}	:	Weighted Digraph
\mathcal{V}	:	Index Set of Nodes
\mathcal{E}	:	Edge Set of Paired Nodes
\mathcal{A}	:	Adjacency Matrix
$\mathbb{R}^{N \times N}$:	Set of N Dimensional Square Matrices
\mathcal{L}	:	Laplacian Matrix
\mathcal{D}	:	Diagonal Matrix
G	:	Pinning Matrix
\mathcal{H}	:	Association Matrix
\mathbb{R}^n	:	n Dimensional Space
$\ x\ _p$:	The p-Norm of a Vector x
\mathcal{L}_p	:	Space of Functions (<i>Lebesgue Space</i>)
$\varepsilon_i(t)$:	Tracking Errors
$g(t)$:	Closed-loop Dynamics
$G(s)$:	The Transfer Function of $g(t)$
$E_i(s)$:	Laplace Transform of $\varepsilon_i(t)$
τ	:	The Inertial Time Delay
u_i	:	The Control Input
d	:	The Desired Inter-vehicle Distance

- K : The Feedback Gain Matrix
- c : The Coupling Gain
- e_i : The Cooperative Tracking Error
- ϵ_i : The Deviation between the Red and Blue Curves
- ω_0 : External Disturbance



1. INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Today, the world is witnessing a massive and rapid development revolution in various aspects of life, including industry, information technology, communications, transportation, etc. Thus, people's lives have changed with the progress of time, and this revolution, which is growing like a ball of fire, has become an essential part in the lives of states and individuals, and is no longer a luxury that can be dispensed with.

Transportation has had a great impact on the settlements of human civilization since ancient times. Transport is defined as the system of movement of people and goods. At the present time, people travel over long distances, and when the transportation networks diversify and change, the main means of travel is still land transportation. As for the transfer of goods and commodities from their sources to their marketing places, it is no less important in the field of economic development and growth, according to the economic criterion. The commodity is considered useless and has no economic importance unless it is available in the required place and time.

Mass migrations of animals can be one of the most exciting events in the natural world. Traveling in social groups helps survival. For example, birds traveling in groups have a considerably better chance than a single bird of identifying a predator or other possible danger. Wild creatures often gather together as a means of securing themselves from predators to travel thousands of miles in their quest for food and shelter, and this type of behavior is not limited to some types of animals only but includes all species, including birds, mammals, fish, reptiles, amphibians, insects, and crustaceans. What if we use this same principle of transport in groups on a group of vehicles? The travel of a group of vehicles with each other, leaving a small distance separating two vehicles, is called a platooning or a platoon of vehicles. Since the platoon is the grouping of individuals in a way that provides advantages to the group, for this reason, this work is motivated and shed light on the platoon of vehicles.

The increasing presence of vehicles due to the development of the automobile industry over a century and the change in car designs during these many years had a significant impact on both traffic jams and the environment. That is why the need for a vehicle

platoon that must be at a high level of automation arose. The class of vehicles offers many benefits. The safety of people around the world has always been a growing concern in any transportation system, as the vehicle class allows vehicles to travel closely but safely together. Carbon emissions contribute to climate change, which can have severe and severe consequences such as tropical storms, forest fires, severe droughts, and heat waves on humans and their environment. In the class of vehicles, air resistance is reduced, which leads to significantly less fuel consumption and less pollution.

1.2 LEVELS OF AUTOMATION

In order to assist in controlling the vehicle, mechatronics, and in particular artificial intelligence (AI), are used in a process known as vehicular automation. This relieves the driver of some duties or makes them easier to handle [1]. Platoon driving demands a higher level of automation due to the closer spacing. The vehicles' electrical linkage eliminates the need for human reaction time, allowing them to accelerate and brake simultaneously. The vehicles in a platoon also have automated longitudinal and lateral guiding [2]. Six levels of automation were specified in a policy on automated vehicles that was released by the National Highway Traffic Safety Administration (NHTSA) [3]. The six levels of automation are presented in [4].

- i. Level 0: No automation; the entire driving task is carried out by a human driver.
- ii. Level 1: Driver assistance: One driver assistance system, either automatic lateral or longitudinal control, is in operation, and the human driver is responsible for maintaining awareness of the road environment and carrying out fallback driving duties.
- iii. Level 2: Partial automation: One or more automated lateral and longitudinal control driver assistance system(s), while the human driver must constantly be aware of the surroundings and conduct fallback driving duties.
- iv. Level 3: Conditional automation: The car drives itself, but it can also need the driver to take over for backup driving duties.
- v. Level 4: High automation: the car continues to drive on its own even if the human driver ignores the car's pleas for help.
- vi. Level 5: Complete automation.

1.3 VEHICLE PLATOONING

1.3.1 Overview

In the military, a platoon is defined as "a division of a company of soldiers, often led by a lieutenant." In other words, a company of soldiers controls its behavior and movement in accordance with the orders of the lieutenant. Military behavior might be viewed as the ideal example for driving on highways because it is recognized for and is a symbol of discipline, obedience, and control [5]. A group of vehicles driven by the leading vehicle, which is usually the first vehicle travel together as one unit, with short distances separating each two vehicles, is called a platoon of vehicles. Sometimes vehicles need to travel long distances on highways, where these vehicles can be passenger cars or trucks, and since the security of individuals and goods is one of the crucial aspects and has the highest priority in any transportation system, hence the need to travel in safer conditions, which is manifested in platoon of vehicles.

1.3.2 Model of Vehicle Platoon Structure

Members of a platoon can be divided into four categories based on their geographical position and functionalities: leader, relay, tail, and member [6]. The leader vehicle is the first vehicle in the platoon, it is responsible for establishing and managing the rest of the vehicles. All other vehicles in the platoon must move in accordance with the leader vehicle's reference movement. The tail vehicle is positioned at the end of a platoon. In order to establish a connection with the following platoon, the tail vehicle must serve as a crucial hub for inter-platoon communication. Moreover, the member vehicle is one of the platoon's vehicles which is neither the leader nor the tail of a platoon. Any vehicle in a platoon can serve as a relay vehicle, which is in charge of helping the leader vehicle spread communications across all the other vehicles in the platoon [7]. Figure 1.1 illustrates the four main structures of a vehicle platoon.

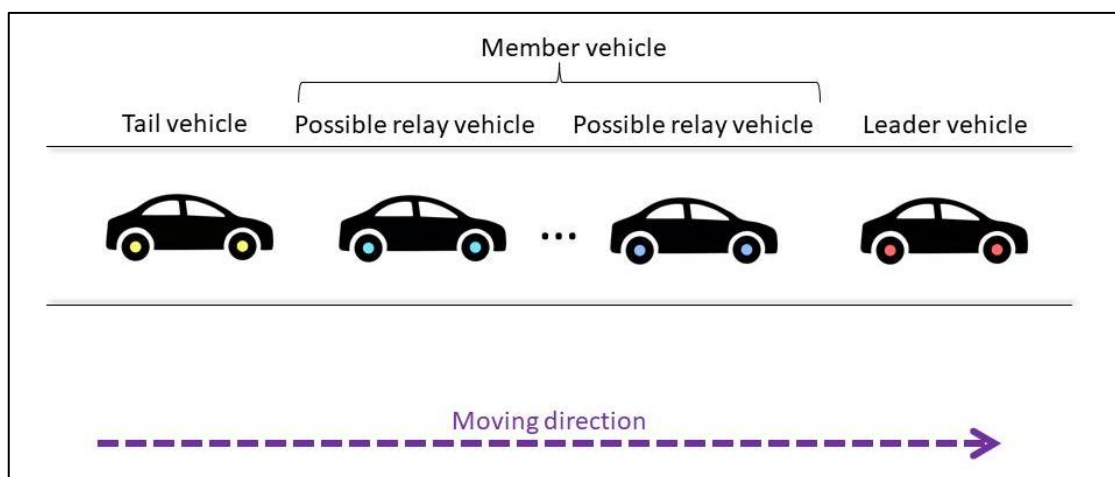


Figure 1.1: The Four Main Components of a Vehicle Platoon.

1.3.3 Platooning Manoeuvres

One of the most important aspects of platooning is manoeuvring [8] - [10]. A manoeuvre is a set of carefully thought-out and executed driver actions such as the formation, operation, and dissolution of platoons. Vehicles must be able to join or leave a platoon at any moment, and platoons must be formed, maintained, split up, and finally pulled apart [11].

In the vehicle platoon, the leader organizes all kinds of manoeuvres. As for the followers, when carrying out any manoeuvre, they need to obtain the leader's approval, meaning that the leader is responsible for giving instructions to each vehicle belonging to him, while keeping the same characteristics when forming the platoon, and he denies any manoeuvre to increase the size of the platoon as determined at the beginning formation.

The joining, leaving, merging, and splitting operations are the most crucial actions that the vehicle platoon takes.

There are some similarities between the joining and leaving manoeuvres. During a joining manoeuvre, one or more vehicles from outside the platoon ask to join. A vehicle from the platoon may request to leave the platoon during the leaving manoeuvre. In both cases, the vehicle that wants to join/leave the platoon sends the packet request to the leader. It is usually of the multi-hop type and contains the manoeuvre identifier and the addresses. Once the leader has given the vehicle permission to join the convoy, the vehicle immediately changes its lanes and it is traveling to join the platoon at the location designated for it in the (front, middle, and rear). As for the vehicle that will leave, it changes its lane and is considered free after that. After the joining/leaving manoeuvre is

completed, the leader arranges the new platoon situation and sends messages to the followers to secure the movement of the platoon.

When the size of the platoon exceeds the maximum size allowed, the leader initiates the split manoeuvre by designating a new leader for the final set of vehicles, who then takes charge of and reorganizes his platoon. In contrast, two small platoons moving in the same lane are united into one platoon during the merging manoeuvre.

1.3.4 Platooning Benefits

The advantages of platooning are one of the main reasons for such widespread attention worldwide.

1.3.4.1 Enhancement of road capacity

Because each vehicle moves at a constant speed and keeps a constant small intra-vehicle distance ahead, road capacity can be increased while traffic congestion can be significantly reduced [12].

1.3.4.2 Reduction of environmental effects

Platooning reduces the distance between the vehicles, which lowers the aerodynamic push and drag forces that prevent the vehicle from moving ahead [2].

1.3.4.3 Increased safety

Because a platoon has closer headways and lower speed variability than typical traffic flow, platoon-based driving may greatly increase traffic safety and efficiency. Furthermore, vehicles periodically transmit a beacon message to their immediate surroundings to indicate their kinetic status [13].

1.3.4.4 Improved driver comfort

The comfort of the driver can be increased depending on how many automated functionalities are present; for example, the driver may assign some driving duties to others. This can reduce tension and let the driver change their concentration, especially on long highway drives. Due to vehicle platooning's ability to regulate traffic flow, comfort is further enhanced. When compared to vehicles driven by humans, speed changes are typically less jarring [14].

1.3.5 Platooning Projects

A description of the main platooning efforts around the world can be found in this section. In-depth studies and trials were carried out in the USA, Europe, and Asia to assess the advantages and viability of platooning [15].

- i. As far as we are aware, the Partners for Advanced Transit and Highways (PATH) program in California's late 1980s was where the first platoon control techniques were used [16]. An empty two-lane motorway in San Diego was used for the experiment and platooning of between three and eight automated trucks traveling at a speed of roughly 96 km/h and each weighing 25 tons was used as can be seen in Figure 1.2. To observe how aerodynamics affected fuel savings, the platooning drove with a gap distance of 6.3 meters [17]. The California PATH program suggested Cooperative Adaptive Cruise Control or CACC as a technique to get lower inter-vehicle distances [18].



Figure 1.2: California PATH Project [19].

- ii. Figure 1.3 shows an illustration of the European project Promote CHAUFFEUR I and II. The driving experiment tests with three large trucks were carried out via the Brenner Pass, which runs across the Alps between Austria & Italy [20].



Figure 1.3: Promote CHAUFFUR Project [19].

- iii. In the KONVOI project, a group of German researchers from the RWTH Aachen University created a platoon of four heavy vehicles between 2005 and 2009. The project's goals were to increase transportation capacity while lowering fuel consumption. In their platoon, which was also tested on German roadways, a human driver operated the lead vehicle, which was followed by three autonomous trucks with a 10 m distance [20]. Figure 1.4 illustrate the project.



Figure 1.4: KONVOI Project [19].

- iv. The 2008-launched Energy ITS (Intelligent Transportation System) Project uses ITS technologies to save energy and mitigate global warming. On a test vehicle and along

a highway before it is open to the public, a platoon of completely automated heavy trucks is currently capable of lane changes as well as steady state driving at 80 km/h with a spacing of up to 4 m [21] as can be seen in Figure 1.5.



Figure 1.5: Energy ITS Project [20].

- v. In order to create vehicles that can achieve safe and effective platooning behavior through communication with one another, industry and academia are working together as part of the 2011 Grand Cooperative Driving Challenge (GCDC) [22]. The 2011 GCDC's objective was to hasten the development, integration, demonstration, and deployment of cooperative driving systems based on the latest in sensor fusion and control technology as well as vehicle-to-vehicle and vehicle-to-infrastructure communication infrastructures [23]. An illustration of this project can be seen in Figure 1.6.



Figure 1.6: GCDC Project [4].

- vi. The Safe Road Trains for the Environment (SARTRE) program, sponsored by the EU, deployed a platoon on a highway, with a lead vehicle and many more autonomously driving vehicles following closely behind. The trial showed that the platoon can travel at speeds of up to 90 km/h with a maximum 6-meter distance between the vehicles [6]. Figure 1.7 depicts this project. Using a manually controlled truck followed by autonomous passenger cars, the study exhibited a platoon of both trucks and cars traveling together on a highway [15].



Figure 1.7: SARTRE Project [24].

- vii. The Distributed Control of a Heavy-Duty Vehicle Platoon (DCHDVP) and iQFleet nationwide platooning programs were undertaken by the Swedish truck manufacturer SCANIA. The Swedish Royal Institute of Technology and SCANIA collaborated to start the DCHDVP. Its aim was to investigate the feasibility of autonomous control of a vehicle in a platoon while maintaining passenger safety. The development of techniques to assist the movement of several platoons on highways and methods to cut fuel consumption are the main goals of iQFleet's platooning research [24]. The project illustration can be seen in Figure 1.8.



Figure 1.8: Platoon Project for Truck Manufacturer SCANIA [25].

viii. The project COoperative dynamic forMation of Platoons for sAfe and eNergy-optImized gOods transportation (COMPANION) is a European project established between the years 2013-2016. In order to produce truck platoons that are acceptable to other road users, as well as economic, legal, and standards challenges, this project explored truck platoon development and management. [2]. COMPANION project illustrated in Figure 1.9.



Figure 1.9: COMPANION Project [19].

- ix. 19 different businesses collaborate in multi-brand platooning scenarios as part of the ENabling SafE Multi-Brand pLatooning for Europe (ENSEMBLE) project. The initiative, which began in 2018, aims to establish guidelines for multi-brand platooning, including rules for maneuvering, operational situations, and communication [19].
- x. The first business to commercialize platooning technology for commercial trucks is Peloton Technologies, a US-based connected and automated vehicle technology company [24].

1.4 PROBLEM FORMULATION

The vehicle platoon has circulated a lot in recent years due to its many advantages and its important role in safety. The way a vehicle communicates with another is through a specific structure or topology. The focus of this thesis is on proposing a new topology for vehicle platoons, as well as in particular, testing it under several scenarios. Although the rapid development of the technology and communications sector many topologies appeared, but communication cost reduction was not considered. In our topology, cost minimization and assuring connectivity to every vehicle in the platoon are our two main goals.

1.5 RESEARCH OBJECTIVES

In this thesis, we present a detailed study of a new topology in the vehicle platoon that takes into account cost reduction while maintaining the necessary efficiency and reaching all members of the platoon. This proposed topology was compared with a pre-existing topology, and the comparison showed that the new topology has a significantly lower cost and the same efficiency. A practical simulation of this new topology was also carried out in several scenarios while increasing the number of vehicles in the platoon, including the movement of vehicles on a straight road, and a disturbance that affects the platoon leader, in addition to a platoon moving on a curved road.

1.6 THESIS ORGANIZATION

This thesis consists of five chapters. Chapter 1 is the introduction. General introduction, background, and motivation of the vehicular platoon have been given a summary of its structure, operations, features, and existing platooning efforts across the world. Chapter 2 starts with a description of the vehicular platoon communication system. It is designated to the main technologies and communication, types of messages, moreover the sensing requirements in a platoon. In Chapter 3, a description of the most prevalent vehicle platoon topologies has been provided. Furthermore, a brief introduction to string stability and disturbances has been provided. Chapter 4 shows our system model and then presents our methodology. The simulation and the summarized results are also mentioned in this chapter. The last chapter is the conclusion and recommendations for future work.

2. VEHICULAR PLATOON COMMUNICATION

2.1 INTRODUCTION

Platooning relies heavily on wireless communications between members to provide digital links between them. These digital links are used to maintain the structure and safety of the platoon [26].

Therefore, this chapter provides the background information, which helps in the understanding of our research. First, we provide a general overview of the communication system used in the vehicular platoon, followed by the concept of VANET. Later V2V, V2I communications will be described. Finally, we present the sensing and communication technologies in vehicular platoon.

2.2 VEHICULAR PLATOON COMMUNICATION SYSTEM

A communication system that connects the vehicles must be created in order to gain overall control over the platoon. When the safety standards are taken into account, this offers some substantial technical issues and is probably going to need a backup communications system. [27]. Vehicle systems depend on the information-sharing technologies that will be used, such as V2V and V2I communication.

2.2.1 Vehicular Ad-Hoc Network

A group of devices that build a network on their own is known as a wireless ad hoc network (WANET). Ad hoc refers to decisions made quickly or only temporarily [28]. Mobile Ad Hoc Network (MANET) is a member of the WANET family.

MANET is a collection of autonomous mobile nodes that uses a multi-hop wireless network, in which a node can move around freely and serves as both a host and a router [29]. The MANET has no pre-existing infrastructure and is often designed to function as a standalone network [30].

Vehicular Ad-hoc Network (VANET) is a subcategory of MANET. VANET is a wireless ad-hoc network that achieves information exchange among vehicles. Vehicle platoon can benefit from data exchange allowing shorter inter-vehicle distances with no lack of safety [31]. Wide limits of applications that are supported by VANET such as safety, prevention of collisions, dynamic route scheduling, blind crossing, and real-time traffic condition monitoring [32]. VANET is a self-organizing decentralized network consisting of a large

number of nodes that are mobile vehicles and communication towers called Road Side Unit (RSU) located on roadsides. The movement of the nodes is the key difference between VANET and MANET where in MANET the nodes can move in any direction however, the nodes can only move in the predetermined road in VANET. Additionally, the speed of the node has an obvious difference between these two concepts as in MANET the speed is very slow compared to VANET [33]. Figure 2.1 compares the differences between VANET and MANET for various parameters.

Parameters	VANET	MANET
System Production Cost	Expensive	Cheap
Reliability on the Network	High	Medium
Mobility of Nodes in Network	High	Low
Mobility Patterns of Nodes	Regular or periodic motion	Irregular motion
Multihop Routing Support	Weakly available	Available
Addressing Scheme Used in Network	Location based addressing	Attribute-based Addressing
Geographical Position Acquirement	Using GPS devices	Using ultrasonic devices
Lifetime of Nodes	Depends on vechile lifetime	Depends on resouce power
Density Of Nodes	Dense and frequently variable	Sparse

Figure 2.1: Differences between VANET and MANET [28].

Communications in VANET networks can be classified into two types Vehicle-to-vehicle and Vehicle-to-Infrastructure.

2.2.2 Vehicle-to-Vehicle Communication

Over the past years, with the rapid development of communication technology notably wireless communications; V2V networks are increasingly becoming common. The vehicle-to-vehicle (V2V) is a communication technique allowing vehicles to communicate directly with each other. Communication in this technique is achieved between vehicles on the roads without any infrastructure to avoid the high costs of it. Communication in this mode is achieved between vehicles on the roads without any infrastructure to avoid high costs, but each vehicle must be equipped with a Global Positioning System (GPS) device, sensors, network equipment, a digital map that includes road information, and computer equipment. V2V is considered as a warning step for vehicles in case of impending danger. Figure 2.2 depicts V2V communication.



Figure 2.2: V2V Communication [32].

2.2.3 Vehicle-to-Infrastructure Communication

Vehicle-to-Infrastructure (V2I) communication is generally used together with V2V, when a vehicle is far away from Road Side Unit (RSU). V2I is a wireless communication technique between vehicles and infrastructure, targeting to collect and gather driving recommendations data. It requires large bandwidth links between vehicles and roadside units to maintain communication in heavy traffic situations. These units send messages using public broadcasting to all vehicles located in their vicinity, and these units are

usually placed every 1 km or less along the entire road. Figure 2.3 depicts V2I communication. VANET is shown in Figure 2.4 using both V2V and V2I technologies.

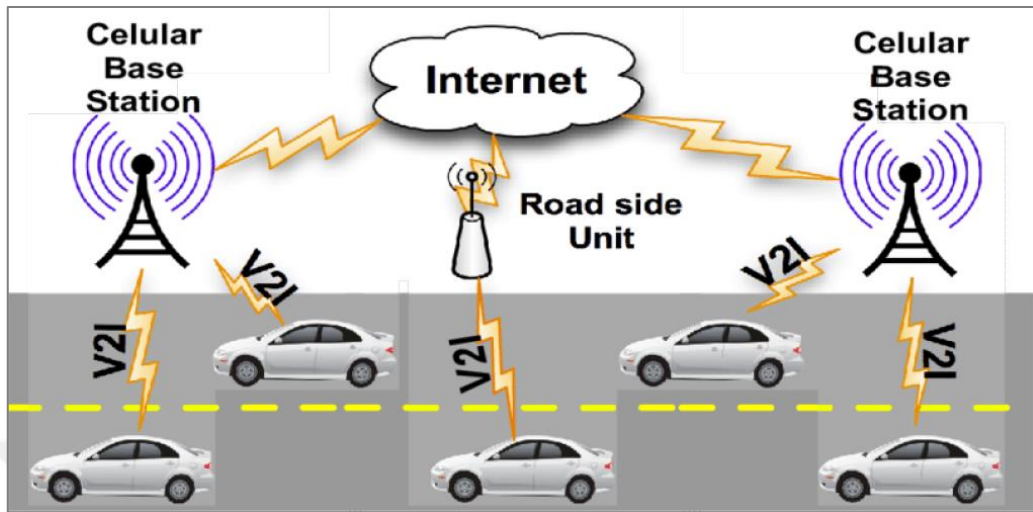


Figure 2.3: V2I Communication [32].

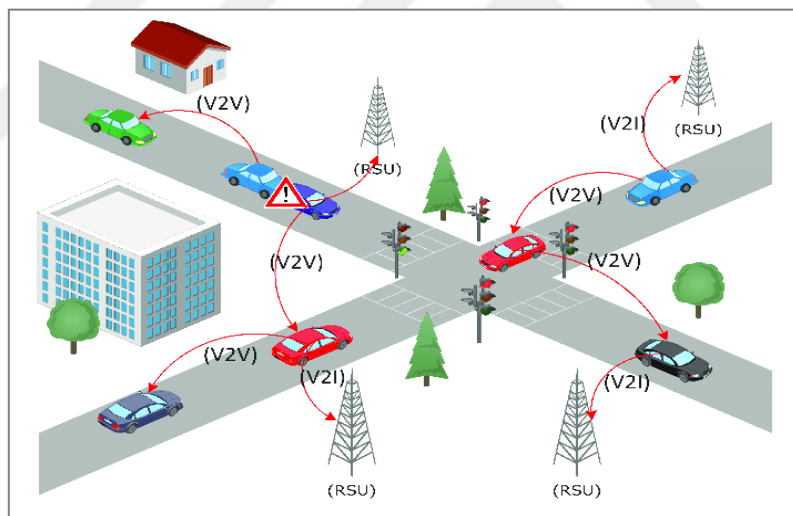


Figure 2.4: VANET with V2V and V2I Technologies [32].

The Institute of Electrical and Electronics Engineers (IEEE) has defined a communication standard called 802.11p, or standard for Wireless Access in Vehicular Environment (WAVE). This standard provides several types of services that are provided to vehicles using either V2V or V2I communications. These services include safety messages such as accident alerts and traffic information aimed at preserving people's lives and improving movement on the road. The second type is service messages such as access to the Internet,

weather news and inquiries about service centres. The WAVE principle uses the multichannel principle to deliver both security messages and service messages, as it categorizes messages with different priorities. WAVE is based on Dedicated Short Range Communication technology or DSRC for short, which includes seven channels of 10 MHz bandwidth each and operates at 5.9 GHz. The DSRC spectrum band and its channels are depicted in Figure 2.5 according to the Federal Communications Commission (FCC) channel allocation. The FCC has designated the 5.850 MHz to 5.925 MHz range as the DSRC band. For such transportation security applications, the 5.9 GHz band has a range of 75 MHz specified by the FCC. Here, the 5.9 is divided into seven 10 MHz channels. As the control channel, one channel is reserved for messages of caution and alert. The remaining six are intended for all other necessary services, while some channels on the periphery might be left unused for later usage. Thus, these are referred to as service channels. Depending on the needs, these channels might also support various data exchange rates. The control channel (CCH) is channel 178, and the service channels (SCH) are channels 174, 176, 180, and 182. The channels 172 and 184 are not in use. It is important to be aware that frequencies vary in the US, Europe and Japan [34]. WAVE devices operate by default on the CCH, which is dedicated to high-priority applications and system control messages. Only the WAVE notification frame is allowed to be sent over CCH while other management frames are sent over SCH.

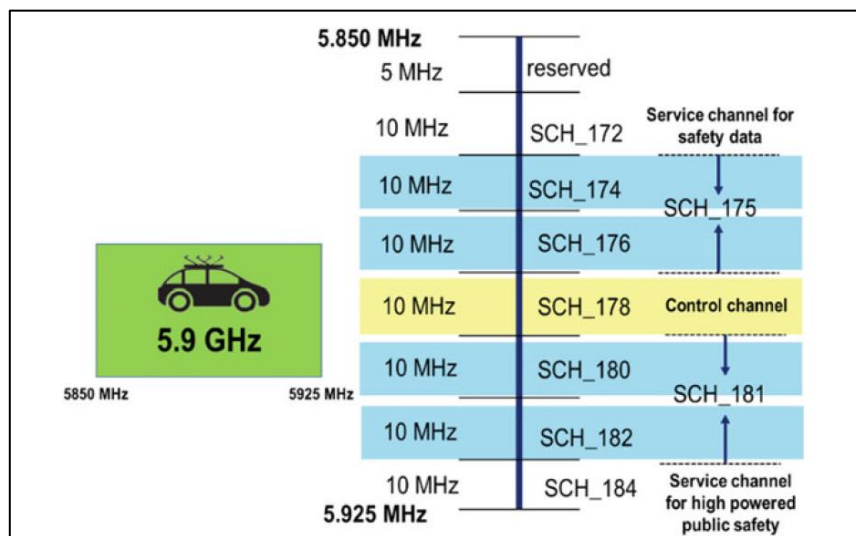


Figure 2.5: DSRC Spectrum and its Channels [34].

2.3 MESSAGES CATEGORIES IN VEHICULAR ENVIRONMENT

Two types of safety-related messages are broadcasted in vehicular environments; that is, periodic and event-driven messages. Beacons are the first kind of messaging, which are used by vehicles to communicate with other vehicles about their present mobility status on a regular basis. They are sent through periodic broadcasts include time-critical information, it doesn't always contain the same information nevertheless, it includes information about position, speed, the direction of travel, heading, etc. This information, which can change rapidly, are always sent and disseminated at a frequency of 10 Hz, i.e. every 100 milliseconds [8]. The beacon's structure is shown in Figure 2.6. A vehicle in the platoon is identified by its vehicleId member, which is set to the same value as the relayerId and is therefore ignored. At each beacon, seqN, a sequence number, is raised [35].

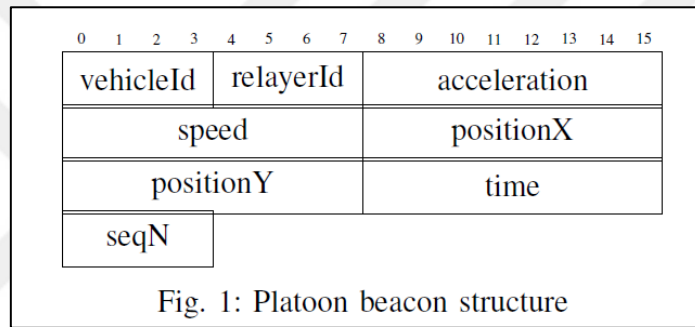


Figure 2.6: Beacon's Structure [35].

Basic Safety Messages (BSMs) and Cooperative Awareness Messages (CAMs) are the names given to beacons in the US and Europe, respectively.

With the aid of safety beacons, nearby vehicles can be accurately localized or positioned [36]. As time-sensitive information, beacons should be distributed with the least amount of latency, packet loss, and congestion possible. When numerous vehicles broadcast the beacon message, a beacon broadcast storm might occur that results in congestion and packet loss [37]. Figure 2.7 depicts the format of a beacon message. The beacon message has a set size of 96 Bytes, including the header. Platoon Id and Platoon depth fields are added to the beacon messages to support platooning. Platoon depth is an integer that indicates the position of the vehicle inside the platoon, and platoon id is a distinctive string that is used to distinguish between several platoons [38].

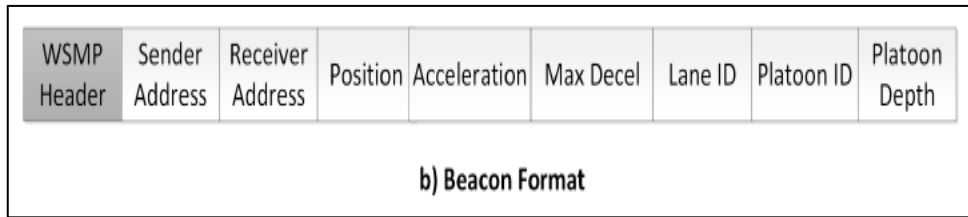


Figure 2.7: The Format of the Beacon [38].

The second type of messages is Decentralized Environmental Notification Message (DENM) is the event-driven messages that are transmitted at the detection of a traffic event or road hazard [39]. Taking the advantage of DENM when the driver has prior knowledge of the imminent danger that awaits him on the road, of course, he will take the appropriate and correct action, which will protect him from accidents that will occur if he did not know in advance of their existence. Furthermore in critical driving situations where vehicles can be very close together, missed or delayed messages can have serious consequences. High demands are placed on the timing and dependability of the underlying communication protocols since both types of messages include data that is extremely time-sensitive [40]. All types of messages are broadcasted on the CCH channel dedicated to cooperative road safety.

2.4 COMMUNICATION TECHNOLOGIES IN VEHICULAR PLATOON

Sensor suites and communication technologies are used by vehicles to learn about their surroundings. From Figure 2.8 the commonly used communication technologies and sensor equipment in the vehicle environment can be illustrated. It's important to remember that efforts are still being made to offer the best suitable communications that are accompanied as reliable, fast, and effective as possible.



Figure 2.8: Sensing and Communication Technologies for Vehicle Platoon [24].

- i. Global Positioning System (GPS): it is a global radio navigation system, which began to work and be designed in the US Department of Defence in 1973 AD, in order to use it with high accuracy to cover military needs. Today, the system is used in other civil applications such as directing civil aircraft and marine navigation, applications in the field of geology and measurements of ground cracks, and also one of its civil uses is in vehicles, where it was used in vehicles for the first time in 1996. GPS consists of three basic units: satellites, ground stations, and receivers. A GPS tracking unit is installed in the vehicle. This tracking unit or receiver receives GPS signals from satellites, and the processor in the device translates these signals. The receiver is able to determine several vehicle attributes including speed, distance travelled, ignition status, door status, breakdown status, and other information. So this information and data from GPS satellites are collected as unified transmission data and are translated, encoded and transmitted to the special control centre.
- ii. Ultrasonic Sensors: Vehicle sensors for near object detection include sonar or ultrasonic sensors. For very close range, up to 2 meters or fewer, they offer direct distance measurements. The capacity of ultrasonic sensors to function in inclement weather, such as snow and fog, is its greatest advantage [24].
- iii. LiDAR: which stands for Light Detection and Ranging, is a laser-based system. Distance measurements are made using a remote sensing device. It makes use of active

sensors that produce their own light from a source of energy. By sending out a pulsed laser beam of light and timing how long it takes for the pulse to be reflected back, it operates on the Time-Of-Flight (TOF) principle [41]. The system uses unique techniques to produce three-dimensional images of the identified items, which are primarily used to calculate distances to both fixed and moving objects.

- iv. **RADAR:** The term "RADAR" stands for "Radio Detection And Ranging," which refers to the use of radio waves for object localization and detection of objects. To determine the speed of the surrounding objects and the amount of their distance from the vehicle, by sending radio waves from the radar transmitting units, so that the receiver units receive them after a rebound process occurs when they collide with the surrounding objects, as this is translated later to indicate the amount of speed and relative location. It is also worth mentioning that according to the range they cover, the radars used in vehicles are categorized into the following categories:
 - a. **Short-range radar:** This radar operates on radio waves with a frequency of 24 GHz, which are used for short-range distances. This sort of radar, which has an estimated range of thirty meters, can be used to identify blind spots when driving, as well as objects nearby for parking assistance.
 - b. **Radio waves at a frequency of 77 GHz** are utilized by long-range radar to transmit signals over distances that are roughly 150 meters or more. A broader field of vision can be employed with this kind of radar to find items. It also establishes traffic alarm systems when driving
- v. **Cameras:** A camera creates a digital image of a covered area using the passive light sensor method. Cameras can identify both moving and stationary things in their immediate area. The primary benefit of cameras over other types of sensors is their capacity to perceive colour and texture [41].

2.5 THE DRIVING MODE CC, ACC, OR CACC

It is vital to explain the concept of Cooperative Adaptive Cruise Control (CACC) and how it developed since a platoon operating in CACC mode has a lower time headway, which increases road throughput while maintaining traffic safety [42].

One of the first driver assistance systems, Cruise Control (CC), was created in 1948 by Ralph Teetor, a blind mechanical engineer. His approach was motivated by the need to end the annoyance of varying speeds as he was being driven down the freeway. His solution involved changing the throttle position with a screw-drive motor. It is worth mentioning that CC is just capable of velocity control.

An extension of the Cruise Control is Adaptive Cruise Control or ACC for short. ACC is a technology that is intended to assist vehicles in keeping a safe following distance while traveling at the posted speed limit. In order to save drivers time, this device automatically changes a car's speed. Automakers and their suppliers installed the initial generation of ACC systems in some luxury vehicles largely to improve driving comfort and convenience with a little possible boost in safety [43]. RADAR is the main and most widely utilized sensor deployed, while other sensors like LiDAR, camera, etc. may also be employed for control input in ACC. The cruise control (CC) system and the adaptive cruise control (ACC) system have both been upgraded by the Cooperative Adaptive Cruise Control (CACC) system. Vehicles can work together to achieve shorter headways and less longitudinal oscillations with the aid of wireless communication devices. CACC has the ability to increase capacity, improve safety, and consume less fuel, according to previous studies. A shuttle bus, logistics freight, and port freight are just a few of the areas where this technology has a wide range of potential applications. These applications have the potential to have a substantial positive impact on the economy and society [44].

3. INFORMATION FLOW TOPOLOGY & STRING STABILITY

3.1 INTRODUCTION

We shall first explain the topologies employed in the vehicle platoon and the role of graph theory. Moreover in this chapter the concept of string stability of vehicle platoon is presented. String stability is affected by the path of communications between the vehicles. Thanks to graph theory, numerous connectivity strategies have been developed. Platoon is impacted by what are known as disturbances, which also have an impact on the string stability. As a result, this chapter is devoted to covering graph theory and how it relates to topologies, which are a type of communication mechanism. We also discussed the different kinds of disturbances since they can have an impact on string instability.

3.2 INFORMATION FLOW TOPOLOGY (IFT) BASED ON GRAPH THEORY

Considering algebraic graph theory is frequently used to explain different network topologies, it is important to understand it and be familiar with the supporting matrices that are employed in our work. After introducing graph theory in this section, we will go through six of the most prevalent topologies.

3.2.1 Graph Theory

In this section, we use graph representation and notations of the system. A weighted digraph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ where $\mathcal{V} = \{1, 2, \dots, N\}$ denotes an index set of N nodes, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ denotes an edge set of paired nodes with (j, i) representing a directional edge (information link) from node j to node i .

Ge et al. (2022) mention that "The digraph \mathcal{G} has a spanning tree if there exists at least one node, called the root, such that there is a path from this node to any other node in the graph" [27]. The adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N \times N}$ denotes a weighted adjacency matrix with $a_{ij} \geq 0$ being the adjacency element (weight) of the edge (j, i) . In addition to the adjacency matrix there are many important matrices associated with the digraph \mathcal{G} :

The Laplacian matrix is defined as $\mathcal{L} = \mathcal{D} - \mathcal{A}$, where $\mathcal{D} = \text{diag}\{d_1, d_2, \dots, d_N\}$ with

$$d_i = \sum_{j=1}^N a_{ij}.$$

To describe the link between the root and the nodes a pinning matrix $G = \text{diag}\{g_{11}, g_{22}, \dots, g_{NN}\}$, is also defined. Finally, the \mathcal{H} matrix which equal $\mathcal{L} + G$ is defined.

It is well acknowledged that the eigenvalues of either the adjacency matrix \mathcal{A} , the Laplacian \mathcal{L} , or the \mathcal{H} matrix essentially represent some global knowledge of the graph.

From the point of view of graph theory, it is natural to consider V2V communication network as a weighted digraph. And since that there is always a link from the leader to each follower hence the network is considered as a spanning tree.

The following section illustrates some of the available ways of exchange information between the platoon's member.

3.2.2 Platoon Communication Topologies

A platoon is not just randomly connected; instead, each platoon has such a specific topology. Typical platoon topologies include: Predecessor following (PF), Predecessor-leader following (PLF), Bidirectional (BD), Bidirectional-leader (BDL), Two-predecessors following (TPF), Two-predecessor-leader following (TPLF) [32].

- i. Predecessor following (PF): As information is sent directly to each vehicle from its predecessor, starting from the vehicle of index 1 to the last one, as in Figure 3.1 (a), this type is thought to be the simplest method used in communication, and as a result, it has been used by many researchers. This type can be considered as unicast communication. Because of this mode of communication, the string's size can be as large as necessary, making it simple for new vehicles to join or leave the convoy with no problems. The distance factor is the most crucial aspect in preventing collisions between vehicles. However, when upstream turbulence develops, the leading vehicle's ability to communicate is limited due to the absence of information other than that transmitted by the prior vehicle [45].
- ii. Predecessor-leader following (PLF): In this type of topology, the vehicle obtains information in two ways, from its predecessor as in PF, and from the leading vehicle as shown in Figure 3.1 (b). Instead of waiting for information to go from one vehicle to

another, this technology enables each vehicle to communicate directly with the leader and modify its status at the moment the information is transmitted [45].

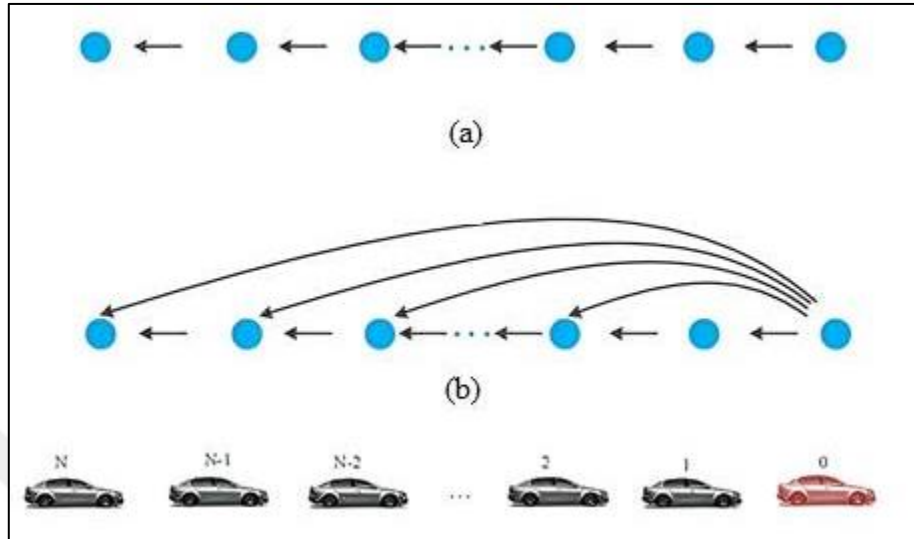


Figure 3.1: (a) PF Topology, (b) PLF Topology [32].

- iii. Bidirectional (BD): To achieve string stability (a feature that guarantees spacing errors won't get worse as they move toward the platoon's tail) in this topology, the vehicle i communicates distance and speed information with its successor vehicle $i+1$ and predecessor vehicle $i-1$ as can be seen in Figure 3.2 (a). Avoiding formation braking is another justification for using this technology to get two-way communication. This method's study of string stability is challenging because, if disturbances do occur, they extend toward the string's beginning and end [45]
- iv. Bidirectional-leader (BDL): If the transmission range is large enough, the leading vehicle will communicate information to every other vehicle. Data is transmitted to every vehicle in the platoon by the lead vehicle using unicast messaging, and it is sent to the lead vehicle by the other vehicles in the platoon using multi-hop communication as depicted in Figure 3.2 (b). BDL is a spanning tree topology when we use graph theory notions, with the leading vehicle serving as the root and the other cars serving as leaves nodes.

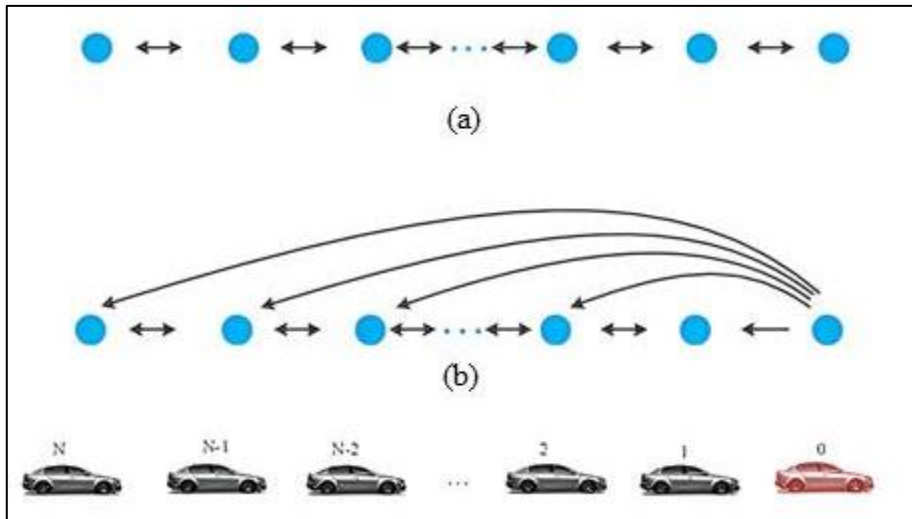


Figure 3.2: (a) BD Topology, (b) BDL Topology [32].

- v. Two-predecessors following (TPF): The PF topology has evolved into this topology. Additionally, as shown in Figure 3.3 (a), information is passed from the leader to the second, from the first to the third, and so forth. This helps improve warnings but requires significant work capacity to deliver information at the required speed [26].
- vi. Two-predecessor-leader following (TPLF): This topology requires an additional transfer process from the previous technology, which is for the leader to transmit his information to each vehicle, as shown in Figure 3.3 (b).

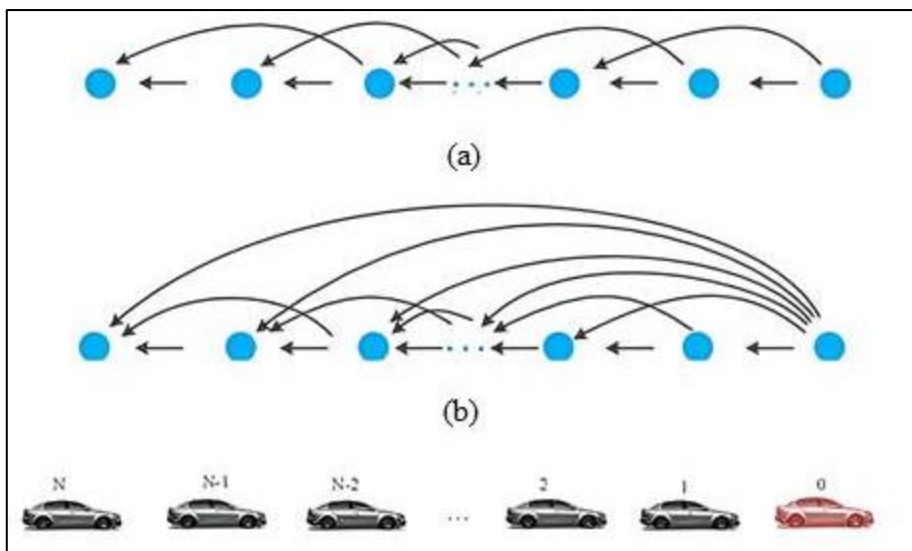


Figure 3.3: (a) TPF Topology, (b) TPLF Topology [32].

3.3 THE EFFECTS OF DISTURBANCES ON THE STRING STABILITY

The disturbances have a significant impact on string stability, resulting string instability. It is referred to as string stable if the disturbances do not increase along the whole platoon, according to [46]. As a consequence, we will define the meaning of disturbances and their sorts as well as the meaning of the word "string stability" and how it relates to disturbance.

3.3.1 Disturbances

A signal that has a tendency to adversely affect a system's output value is referred to as a disturbance. An internal disturbance is one that is produced inside the system, whereas an external disturbance is one that is produced externally and is an input [47]. In particular, internal turbulence in vehicles is issued with a vehicle or its parts, including the radar, brakes, or control logic, whereas road or other vehicles disturbances that affect a platoon are considered external disturbances [5]. Platoons' robustness to external disturbances, also known as disturbance propagation, is a crucial performance indicator [48]. Large spacing errors between inter-vehicles can be produced by small disturbances occurring on one vehicle [49]. We concentrate on two forms of external disruptions that are most frequently discussed in studies. The first kind is sinusoidal disturbances, which have a periodic form, while the second is acceleration disturbance means any variation in the vehicle platoon's acceleration is seen as a disturbance. In [5], types of internal disturbances are mentioned such as reaction time and delays, deviation and noise. Furthermore, road slopes, wind gust, equivalent time delays from wireless connection delays, and discrete data from on-board sensors are some examples of external disturbances [50].

In the chapter 4, more details of these two types of disturbances can be found.

3.3.2 String stability

The vehicles in a platoon are referred to as a "string" because they follow one another and wireless data is used in a feedforward setting. String stability is the controller's capacity to reduce spacing error disturbances as they spread upstream in the vehicle string. A disturbance on one vehicle (such as a change in velocity) is amplified as it spreads upstream to the following vehicles (especially at the tail of the platoon) if the platoon is not

string stable. This can result in collisions, an uncomfortable and unsafe driving experience for passengers and jerky vehicle response [51].

The string stability feature has been extensively researched for platoon control to address this issue. String stability investigations often follow a three-step process [52].

- i. Define the property of string stability mathematically
- ii. Deduce the sufficient criteria using analysis techniques
- iii. Construct controllers that satisfy the sufficient criteria

Vehicle dynamics, information flow topology, the caliber of inter-vehicle sensing and communication, and the inter-vehicle spacing strategy all have an impact on string stability [53].

Various types of definitions and analytical techniques have been proposed in a substantial amount of literature [54], [55], [56].

Using the transfer function, we will adopt the following string stability analysis.

The p-norm of a vector $x \in \mathbb{R}^n$ is given as:

$$\|x\|_p = \left(\sum_{i=1}^n |x_i|^p \right)^{1/p}, \quad p \in [1, \infty) \quad (3.1)$$

$$\|x\|_\infty = \max_i |x_i| \quad (3.2)$$

Given a signal $x(t): I \rightarrow \mathbb{R}^n$,

$$\|x\|_p = \left(\int_I |x(t)|^p dt \right)^{1/p}, \quad p \in [1, \infty) \quad (3.3)$$

$$\|x\|_\infty = \sup_{t \in I} |x(t)| \quad (3.4)$$

are the p-norm and ∞ -norm respectively.

Let's assume that the tracking errors for distance, speed, and acceleration are as follows,

$$\varepsilon_i(t) = x_i(t) - x_{i-1}(t) - L_i \quad (3.5)$$

$$\dot{\varepsilon}_i(t) = v_i(t) - v_{i-1}(t) \quad (3.6)$$

$$\ddot{\varepsilon}_i(t) = a_i(t) - a_{i-1}(t) \quad (3.7)$$

where L_i is the preceding vehicle length.

Let

$$g(t) = L^{-1}\{G(s)\} \quad (3.8)$$

be the impulse response of the system, where $G(s)$ is the transfer function of $g(t)$ i.e.,

$$G(s) = \frac{E_i(s)}{E_{i-1}(s)} \quad (3.9)$$

where $E_i(s)$ is Laplace transform of $\varepsilon_i(t)$

If the two following criteria are met, the system is string stable [57]:

- a. $\|G(s)\|_\infty \leq 1$
- b. The impulse response function $g(t)$ should not change sign, i.e. $g(t) > 0, \forall t \geq 0$

In [52], [57] and [58] more details about string stability can be found.

3.3.2.1 String stability of the CACC system

An essential performance criterion for the CACC controller architecture is string stability. The vehicle spacing error, states, or control input must not magnify upstream through the vehicle platoon in order for the string stability of the vehicle platoon to be maintained. When a vehicle platoon is not string stable, even a little disturbance on one vehicle can spread throughout the platoon and result in uncomfortable or even hazardous driving conditions [59]. A short time gap inside vehicle platoons using sensors and communication technology is made possible by CACC, an extension of ACC (see sec. (2.5)). Thus, it has the potential to result in considerable increases in road capacity and decreases in traffic. Several CACC controllers have been created and proven to suit the fundamental requirement of successful platoon motions while maintaining string stability. The existing CACC controllers, however, are not equipped to handle some potential risks in unexpected events, which could pose a safety risk. Unexpected events, like cyberattacks, might cause regular cruising statuses to be stopped [60]. A platoon using CACC can travel farther in less time while still assuring string stability since it has a quicker reaction time of the following vehicles than regular ACC, which simply uses data from radar sensors [42]. The CACC system was recommended in light of certain research that implies the ACC system may be responsible for the instability of traffic flow.

4. A PROPOSED TOPOLOGY TO REDUCE THE COMMUNICATION COST

4.1 INTRODUCTION

In this chapter, a new topology is proposed. First, a vehicle longitudinal dynamic model is presented. Next, a thorough explanation of the new proposed topology follows and clarifies the difference between it and another topology. For a platoon of four vehicles, the two topologies were examined and compared during a simulation in MATLAB/Simulink to demonstrate the usefulness of the proposed topology. In addition, the platoon's size was extended from four to eight vehicles, and a variety of scenarios were then simulated. The platoon of vehicles was going regularly (i.e., without any disturbances) on a straight road in the first scenario. In the second scenario, however, two different forms of driving disturbances—sinusoidal and acceleration disturbances—were introduced.

4.2 VEHICLE MODEL

Both longitudinal and lateral movement should be accurately regulated while vehicles are traveling over a roadway, for instance, a highway, bridge, ramp, intersection, or U-turn [61]. The lateral controller steers the wheels of the vehicle for route tracking, whereas the longitudinal controller controls the cruise velocity of the vehicle [62]. In our work, the longitudinal dynamic is adopted and the following dynamical system is used:

$$\dot{\bar{x}}_i(t) = A\bar{x}_i(t) + Bu_i(t) \quad , i = 0, 1, \dots, N \quad (4.1)$$

Where:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau} \end{bmatrix} \quad (4.2)$$

The vector $\bar{x}_i(t)$ is defined as $[p_i(t), v_i(t), a_i(t)]^T$, where $p_i(t)$, $v_i(t)$, and $a_i(t)$ are the position, velocity, and acceleration respectively of the vehicle i . Also $N + 1$ is the number of homogeneous vehicles in the platoon, while the parameter τ is an inertial time delay and u_i is the control input.

4.3 THE PROPOSED TOPOLOGY

This study takes into account a homogenous platoon with one leading vehicle and N followers. We suggest a bidirectional topology with two radars or LiDAR placed on each vehicle, front and back, to monitor the status of the neighbouring two vehicles that serve as its successor and predecessor. Although our proposed topology is based on BDL topology, it also considers how to decrease the cost of the necessary communications between the leading vehicle and the followers. To keep costs down, a follower with an odd index can wirelessly communicate with the leader to find out the leader's location and speed status. In order to reflect this, we gave it the name Bidirectional Odd Leader (BDOL), where the letter O stands for the odd number. Our topology has the advantage of significantly lowering communication costs by reducing the number of followers who get information from the leader while maintaining communication with all platoon members. If we let the tail vehicle to exchange information with the leader, we assume that N is an odd number. Figure 4.1 (a) and (b) show the BDL and BDOL topologies, respectively.

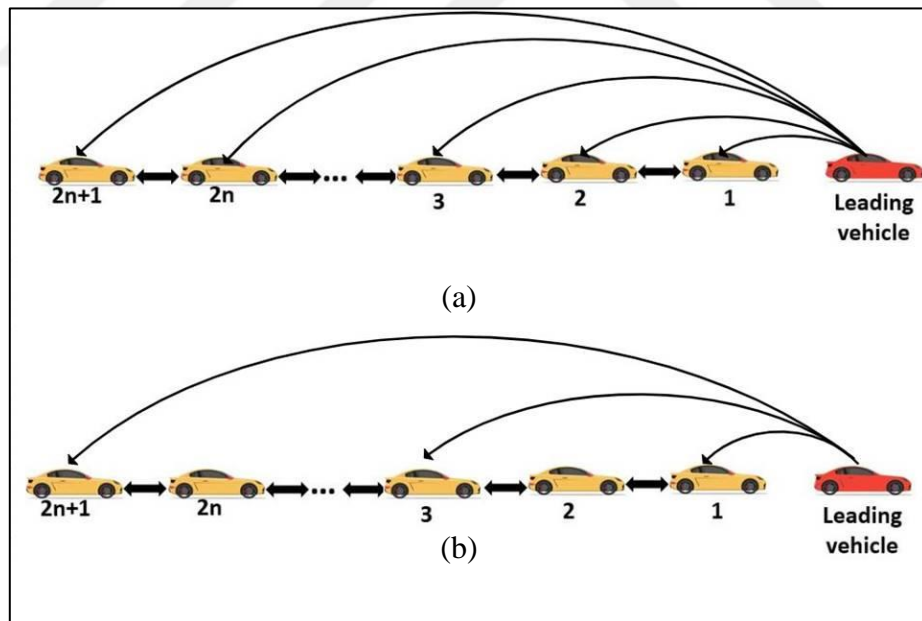


Figure 4.1: (a) BDL Topology [63], (b) BDOL Topology.

4.4 THE PROPOSED TOPOLOGY'S PERFORMANCE

This section conducts a numerical simulation experiment to demonstrate how well our proposed topology performs in comparison to other topologies. We use one of the prototype models studied in [63], namely the BDL topology. For a homogenous platoon of four vehicles, including one leading vehicle and three followers, the simulations were done in MATLAB/Simulink.

The desired inter-vehicle distance $d = 5\text{m}$, the inertial time delay $\tau = 0.25\text{s}$, the feedback gain matrix $K = [1.0000 \quad 2.1211 \quad 0.7494]$, and the coupling gain $c = 1$, while the initial positions for the vehicles 0,1,2,3 are 45, 30,15,0 respectively and the initial velocity for each one is set to be 20 m/s as in [63]. The Laplacian and pinning matrices for BDL and BDOL are given in table 4.1.

Table 4.1: BDL & BDOL's Laplacian & Pinning Matrices.

Topology	Laplacian matrix	Pinning matrix
BDL [63]	$[1, -1, 0; -1, 2, -1; 0, -1, 1]$	$[1, 0, 0; 0, 1, 0; 0, 0, 1]$
BDOL	$[1, -1, 0; -1, 2, -1; 0, -1, 1]$	$[1, 0, 0; 0, 0, 0; 0, 0, 1]$

The control input u_i is represented as:

$$u_0(t) = 0 \quad (4.3)$$

$$u_i(t) = cKe_i(t) \quad , i = 1, 2, \dots, N \quad (4.4)$$

where e_i is the cooperative tracking error defined as:

$$e_i = \sum_{j=1}^N \{a_{ij}(x_j - x_i - d_{ij})\} + g_{ii}(x_0 - x_i - d_{i0}) \quad (4.5)$$

Figure 4.2 shows the result of comparing the performance of each topology. The BDL represented by the red curve while our BDOL topology shown as the blue one.

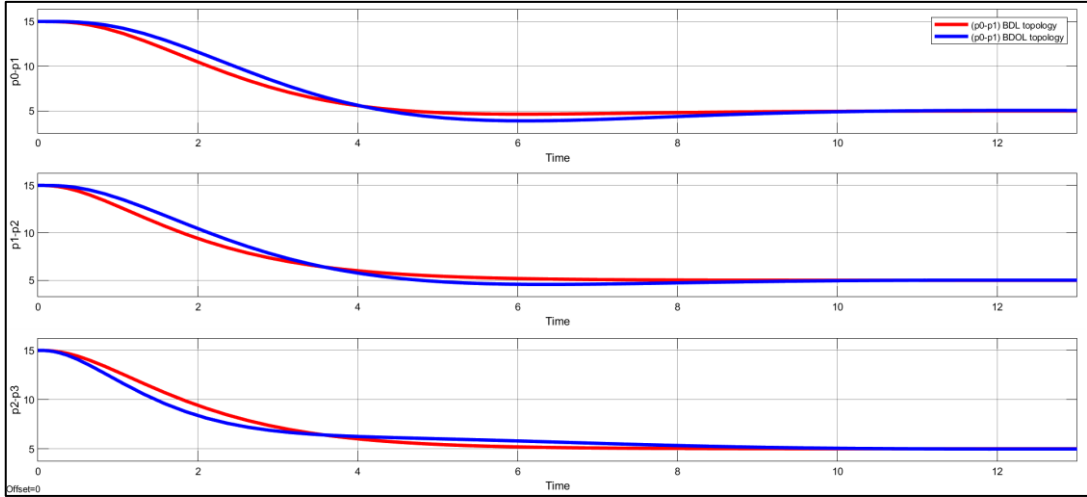


Figure 4.2: The BDL's Performance Compared to BDOL's.

Figure 4.2 shows that the blue and red curves are not significantly different from one another, even at various intervals, and that the calculation results show that the aforementioned relaxation method performs better than BDL topology. If we let ϵ_1 , ϵ_2 , and ϵ_3 denote the deviations between the red and blue curves for the functions $p_0 - p_1$, $p_1 - p_2$, and $p_2 - p_3$ respectively, then we find that of $\epsilon_1 \leq 1.107$ m, $\epsilon_2, \epsilon_3 \leq 1.719$ m. Also we noted that BDOL reaches the steady state faster than the BDL. Since the relaxing technique's primary objective is to cut down on communication expenses, hence our topology is better than BDL topology.

4.5 DISTRUBUTIONS IMPACTING PLATOON

A signal that has a tendency to adversely influence a system's output value is referred to as a disturbance. In contrast to external disturbances, which come from the outside of the system, internal disturbances start inside the system [47]. The topology structure, as opposed to the design of the feedback gains, has a greater influence on how disturbances propagate [48].

Due to the coupled system's interconnected structure, disturbances impacting one vehicle (particularly the leader) may also affect adjacent vehicles and can increase spacing faults, resulting in string instability [64]. Nevertheless, any vehicular platoon member has the same chance of confronting external disturbances [49]. The dynamical system of the leader is an independent system that is unaffected by any followers.

4.6 SIMULATION AND ANALYSIS

One leading vehicle and seven following vehicles make up the platoon. The vehicles are numbered from 1 to 7 advancing down the platoon, with 0 being the lead vehicle index. Without losing generality, we take into account the case of a homogenous vehicle, where $m_i = m (i = 0, 1, \dots, 7)$ with a desirable inter-vehicle spacing of 10 m. Depending on the applications, any value for the mass m may be selected. The control input for the seven followers as in (4.1). As in the earlier section, the parameters τ and K are set. This is the association matrix \mathcal{H} :

$$\mathcal{H} = \begin{bmatrix} 2 & -1 & & & & & & \\ -1 & 2 & -1 & & & & & \\ & -1 & 3 & -1 & & & & \\ & & -1 & 2 & -1 & & & \\ & & & -1 & 3 & -1 & & \\ & & & & -1 & 2 & -1 & \\ & & & & & -1 & 2 & \end{bmatrix} \quad (4.6)$$

Its eigenvalues is presented in table 4.2.

Table 4.2: The Eigenvalues of the Matrix \mathcal{H} .

Eigenvalue	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
Value	0.15	0.58	1.23	2.00	2.76	3.40	3.80

According to [65], the coupling gain c must be chosen to satisfy the condition:

$$c \geq \frac{1}{2 \min_{i=1,2,\dots,N} \text{Re}(\lambda_i)} \quad (4.7)$$

where, $\text{Re}(\lambda_i)$ is the real part of the eigenvalue λ_i . Hence $c \geq 10/3$, we chose it equal to 4.

Table 4.3 displays the initial positions of each platoon vehicle.

Table 4.3: Initial Position of the Vehicles.

Vehicle	0	1	2	3	4	5	6	7
Position	0	-15	-30	-45	-60	-75	-90	-105

To compute the control input $u_i, i = 1, \dots, 7$ using the relation 4.4 one has to compute the Laplacian matrix and the pinning matrix first:

The Laplacian matrix \mathcal{L} is

$$\mathcal{L} = \begin{bmatrix} 1 & -1 & & & & & & & \\ -1 & 2 & -1 & & & & & & \\ & -1 & 2 & -1 & & & & & \\ & & -1 & 2 & -1 & & & & \\ & & & -1 & 2 & -1 & & & \\ & & & & -1 & 2 & -1 & & \\ & & & & & -1 & 1 & & \end{bmatrix} \quad (4.8)$$

while the pinning matrix G is:

$$G = \text{diag}[1,0,1,0,1,0,1] \quad (4.9)$$

The formula (4.5) is utilized to determine the cooperative tracking error e_i . The following formulas calculates the e_i for each of the seven followers.

$$\begin{aligned} e_1 &= x_0 - 2x_1 + x_2, \\ e_2 &= x_1 - 2x_2 + x_3, \\ e_3 &= x_0 + x_2 - 3x_3 + x_4 - 3z, \\ e_4 &= x_3 - 2x_4 + x_5, \\ e_5 &= x_0 + x_4 - 3x_5 + x_6 - 5z, \\ e_6 &= x_5 - 2x_6 + x_7, \quad \text{and} \\ e_7 &= x_0 + x_6 - 2x_7 - 8z \end{aligned} \quad (4.10)$$

where $z = [10, 0, 0]^T$.

4.6.1 Platoon Behavior During Regular Operations

The platoon was being driven while using BDOL topology on a straight road. The initial velocity for all the platoon is set to be 20 m/s, correspondingly the initial acceleration becomes zero. The platoon leader's dynamical system is

$$\dot{\bar{x}}_0 = A\bar{x}_0 + Bu_0 \quad (4.11)$$

where u_0 for the interval $0 \leq t \leq 50$ is designed in two cases:

either equal to zero:

$$u_0 = 0 \quad (4.12a)$$

or time varying as:

$$u_0 = \begin{cases} 0.8 \text{ m/s}^2 & t \in [15,25]s \\ -0.8 \text{ m/s}^2 & t \in [30,40]s \\ 0 & \text{otherwise} \end{cases} \quad (4.12 b)$$

For $t \geq 0$ and for both situations, using BDOL topology yields the simulation results, which are depicted in Figures 4.3, 4.4, and 4.5 (a) & (b), showing how each vehicle in the platoon behaves in terms of position, velocity, and acceleration respectively. It is evident at the beginning (from $t = 0$, up to $t = 10$) that there must be an increase in speed first, followed by a reduction in speed in order to accomplish the goal of maintaining the needed distance between every two successive vehicles.

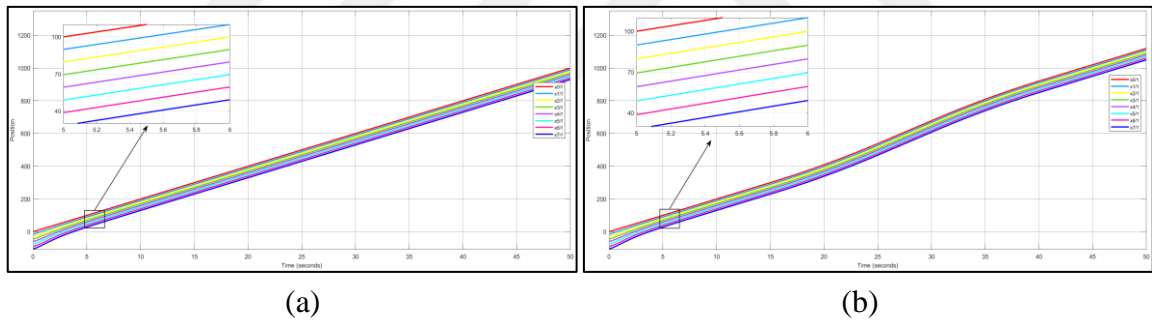


Figure 4.3: Position of Vehicles in Regular Operation when u_0 (a) Zero (b) Time Varying.

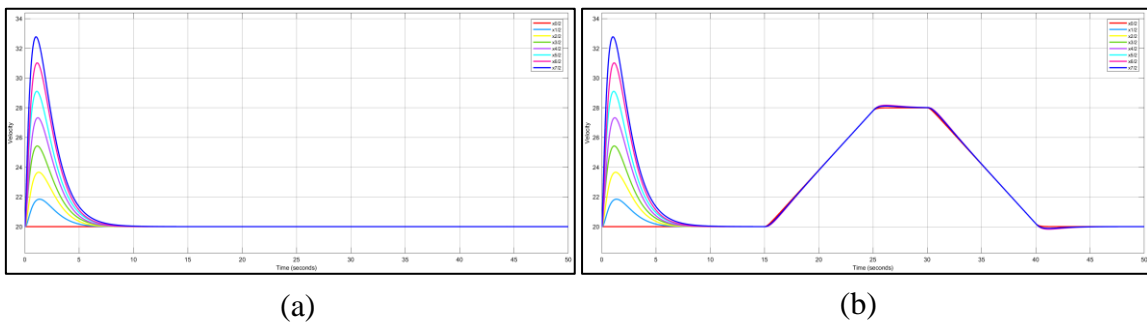


Figure 4.4: Velocity of Vehicles in Regular Operation when u_0 (a) Zero (b) Time Varying.

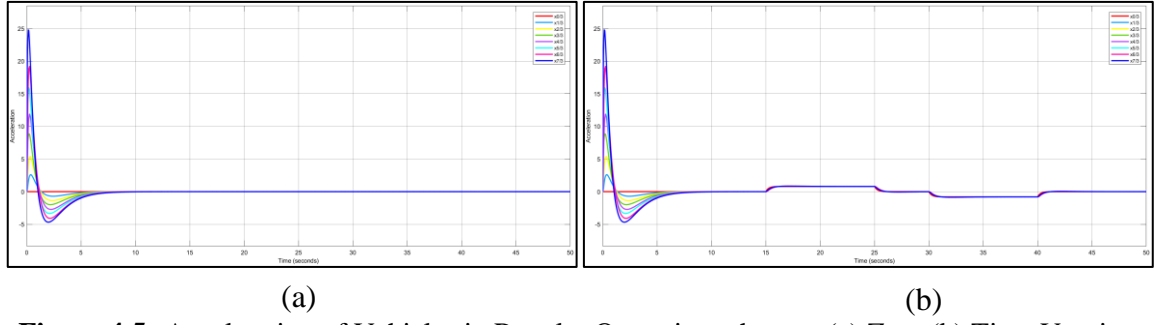


Figure 4.5: Acceleration of Vehicles in Regular Operation when u_0 (a) Zero (b) Time Varying.

The effectiveness of u_0 being nonzero on the behaviors of the vehicle is extremely obvious. According to figure 4.4 b, the leader travels at a constant speed of $v = 20$ from $t = 0$ to $t = 15$ and then accelerates from $t = 15$ to $t = 25$ until the velocity reaches $v = 28$. Then, continuing at this constant speed, as defined by the leader's control unit, until $t = 30$, at which point slowing down begins and the speed becomes $v = 20$ at $t = 40$ and continuing at this steady speed.

4.6.2 Platoon Behavior under Disturbances

Here, we make the assumption that the leading vehicle experiences both external and acceleration disturbances. The same specifications as in section 4.6.1 were applied.

4.6.2.1 Sinusoidal disturbance

As in the previous section, the vehicle platoon was driven on a straight route. The majority of research on string stability solely include the leading vehicle's external disturbances, which are mostly brought on by a gust of wind, rolling resistance, and ground friction [66]. When the lead vehicle experiences certain types of disturbances, its dynamical system will be:

$$\dot{\bar{x}}_0(t) = A\bar{x}_0(t) + B[u_0(t) + \omega_0(t)] \quad (4.13)$$

The leader's control input u_0 is as taken as in section (4.6.1) for two cases, while $\omega_0(t)$ is an external disturbance. We examine the effect of the disturbance of the type $\omega_0 = a_0 \sin(\omega t + \theta_0)$ [67], that imposes in the leading vehicle. As in [68], Let

$$\omega_0(t) = 1.5 \sin \left[\frac{2\pi}{10} (t - 20) \right] \quad (4.14)$$

The initial velocity for all the platoon is set to be 20 m/s, correspondingly the initial acceleration becomes zero.

When applying BDOL topology in this case, the simulation results will be depicted in Figures 4.6, 4.7 and 4.8 which show the position, velocity, and acceleration of each vehicle in platoon.

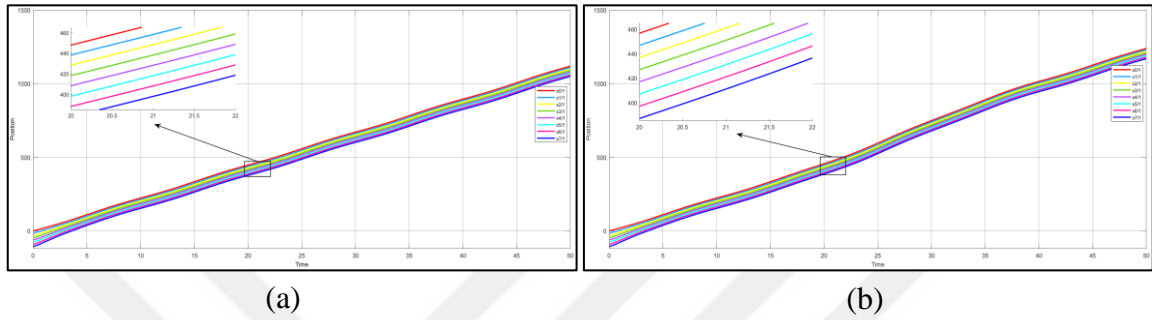


Figure 4.6: Position of Vehicles in Sinusoidal Disturbances when u_0 (a) Zero (b) Time Varying.

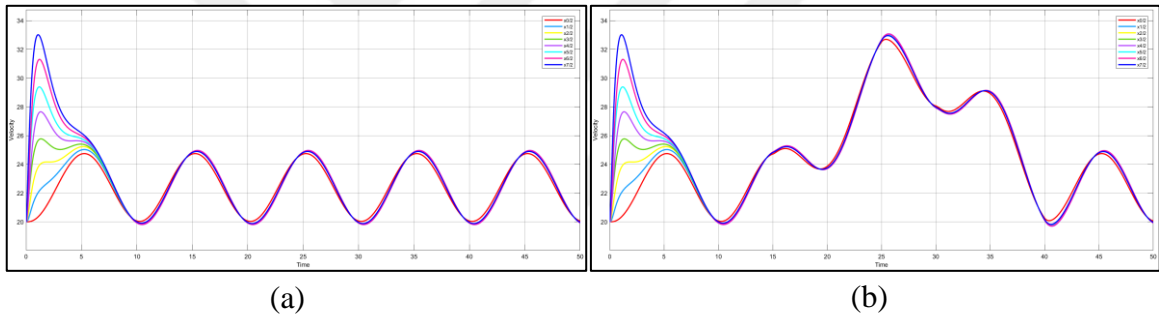


Figure 4.7: Velocity of Vehicles in Sinusoidal Disturbance when u_0 (a) Zero (b) Time Varying.

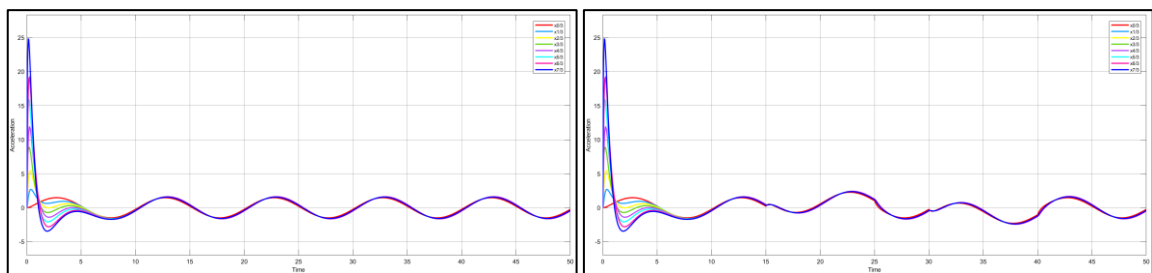


Figure 4.8: Acceleration of Vehicles in Sinusoidal Disturbance when u_0 (a) Zero (b) Time Varying.

Figures 4.7 and 4.8 demonstrates unequivocally that the leader changes speeds to preserve the objective as the leading vehicle is perturbed. All vehicles that follow will change their speeds in accordance with the sinus curve.

4.6.2.2 Acceleration disturbance

The variation in velocity of the leading vehicle in a platoon (which causes an alteration in acceleration) might be regarded as an external disturbance. The state of the road or the weather may be the source of such disruptions.

The Simulation of Urban MObility (SUMO) program was used to start a curved, two-lane road, as shown in Figure 4.9. In 2002, the SUMO traffic simulation program was released. SUMO, a collection of apps, requires a description of road networks and traffic demand. On SUMO road networks, there are intersections, junctions, and traffic lights [69]. The vehicle platoon was driven along the route, with the red-colored vehicle serving as the platoon's leader and the yellow-colored vehicles serving as its members.

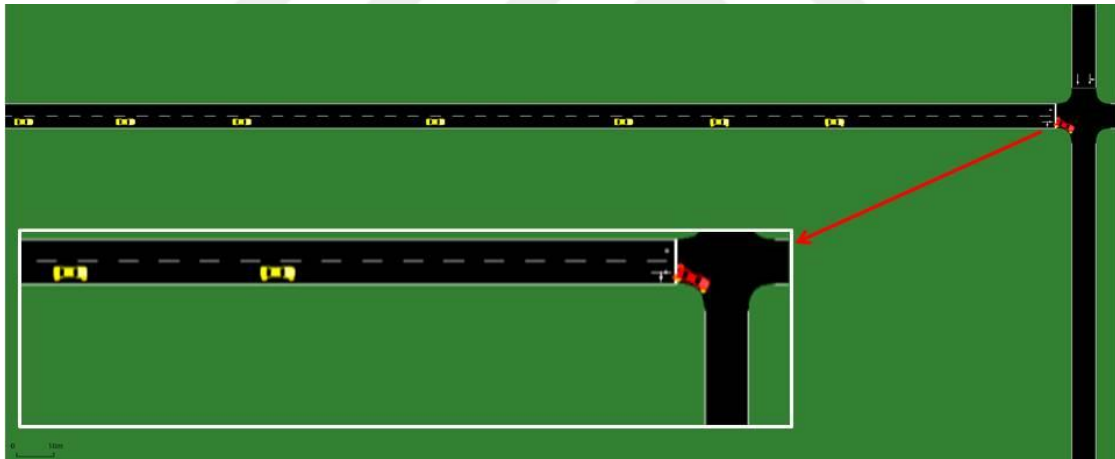


Figure 4.9: The Vehicle Platoon Driven On Two-Lane Road Created in SUMO Simulator.

The velocity change of the leading vehicle is the most significant disturbance in a platoon (or acceleration). In other words, the presence of a cause that prevents the vehicle platoon from maintaining its constant pace constitutes a disruption.

The leader's dynamical system as in (4.1). The relationship between the leader's control input u_0 and velocity (acceleration) is defined as follows:

$$u_0 = \tau \dot{a}_0 + a_0 \tag{4.15}$$

Here, we provide the following definition of the intended trajectory:

$$v_0(t) = \begin{cases} \frac{1}{3}[t^2 - 24t + 155] & t \in [5,10] \\ 5 & t \in [10,15] \\ -\frac{1}{6}[t^2 - 53t + 540] & t \in [15,20] \\ 20 & \text{otherwise} \end{cases} \quad (4.16)$$

The outcomes of using BDOL topology in this situation are as follows: the position of each vehicle in the platoon in acceleration disturbance case is depicted in figure 4.10, while the velocity and acceleration are shown in figures 4.11 and 4.12 respectively.

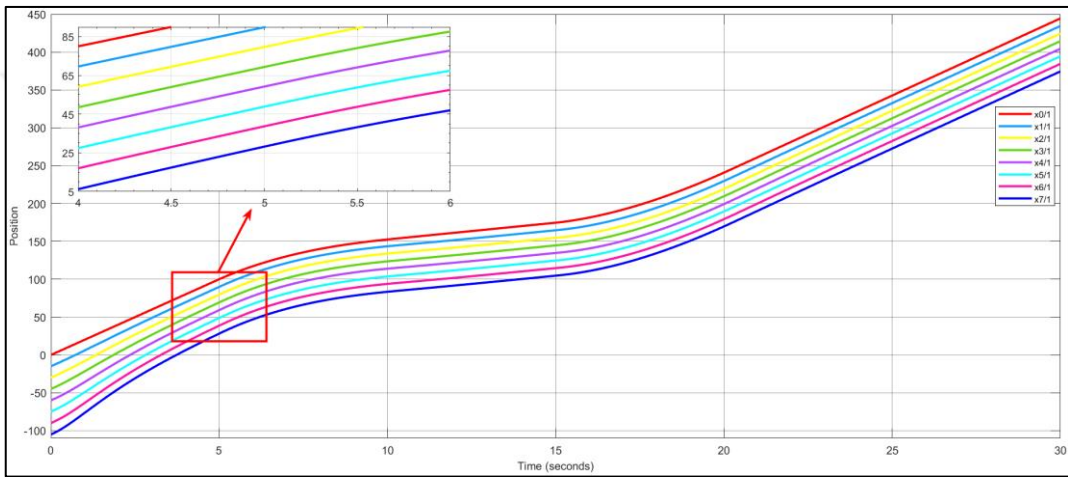


Figure 4.10: The Position of Vehicles under Acceleration Disturbances.

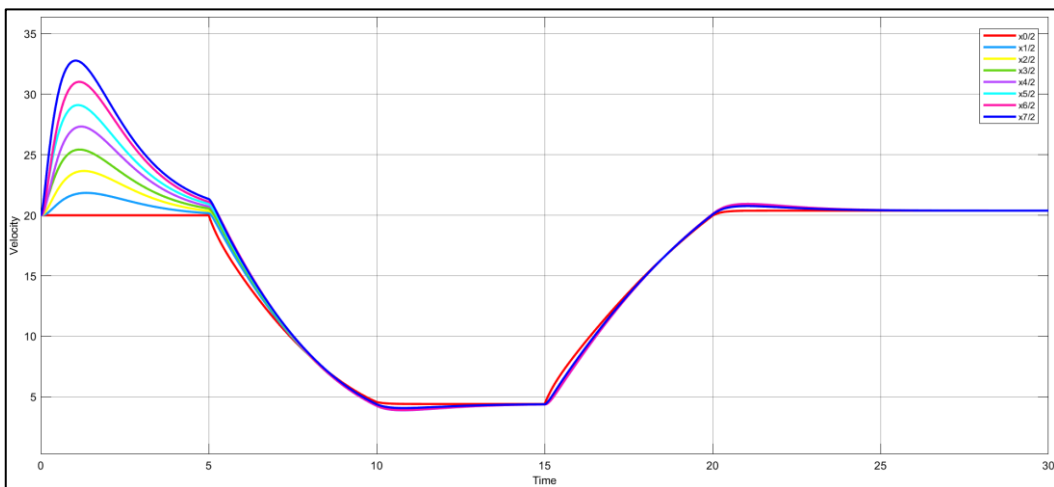


Figure 4.11: The Velocity of Vehicles under Acceleration Disturbances.

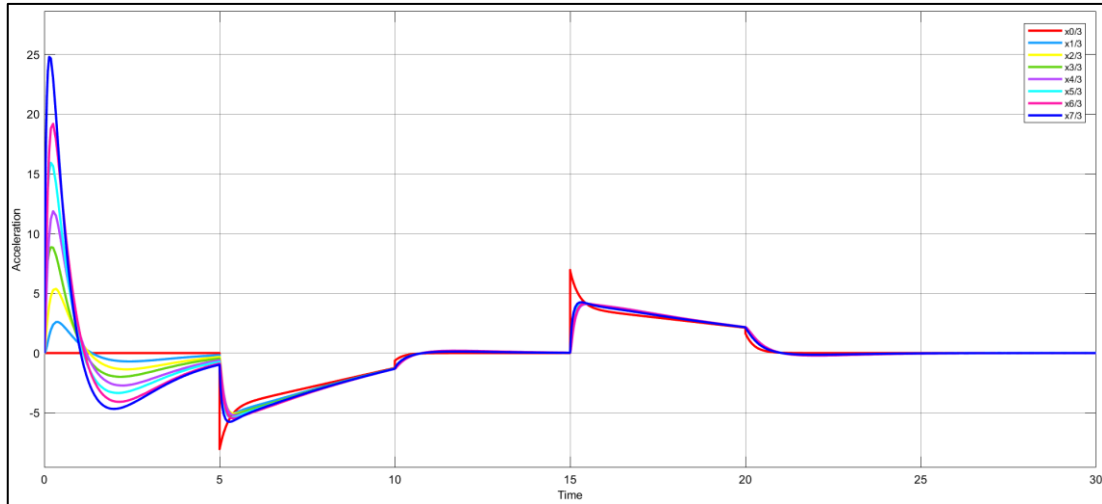


Figure 4.12: The Acceleration of Vehicles under Acceleration Disturbances.

From figure 4.10, it is clear that the distance between every two consecutive vehicles is as designed (10m). Because the road is curved, the leader is forced to reduce the velocity to its minimum value $v = 5$ and then has to use this velocity for a while from $t = 10$ to $t = 15$. For the period $t = 15$ to $t = 20$ accelerating is necessary to return to the planned velocity $v_0 = 20$.

5. CONCLUSION

Because it is crucial and necessary to reduce the communication cost, a novel topology termed BDOL for a homogenous platoon of vehicles was presented in this work. The BDL topology is relaxed in the BDOL, where the communication cost is kept to a minimum. The decrease in the number of communication devices needed, by restricting broadcasting between the leading vehicle and some followers while retaining the distribution of information to all members of the platoon. We assessed the BDOL topology's performance and compared it to the BDL topology in order to establish a trade-off between communication expense and system performance. The outcomes of our experiment demonstrate that while the BDL and BDOL operate essentially indistinguishably, the cost of communication was significantly decreased. Later, several scenarios involving a higher number of vehicles and the BDOL's performance were investigated. The leading vehicle is forced to navigate straight and curving tracks with or without obstructions. The regulation of maintaining distance between two successive platoon members is addressed by the longitudinal aspect of string stability.

In many studies, the simulation results show similar property to the mathematical definition of string stability, hence in each example of our simulation, the string stability of the platoon of vehicles was examined, and our findings demonstrated the potency of the suggested topology.

In this thesis, we dealt with the movement of a platoon of vehicles on a straight road and another curved road. Future work can be done that will deal with the movement of vehicles in a platoon in a more realistic way, either in two or three dimension.

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